Optimum air-demand ratio for maximum aeration efficiency in high-head gated circular conduits

Fahri Ozkan, M. Cihat Tuna, Ahmet Baylar and Mualla Ozturk

ABSTRACT

Oxygen is an important component of water quality and its ability to sustain life. Water aeration is the process of introducing air into a body of water to increase its oxygen saturation. Water aeration can be accomplished in a variety of ways, for instance, closed-conduit aeration. High-speed flow in a closed conduit involves air-water mixture flow. The air flow results from the subatmospheric pressure downstream of the gate. The air entrained by the high-speed flow is supplied by the air vent. The air entrained into the flow in the form of a large number of bubbles accelerates oxygen transfer and hence also increases aeration efficiency. In the present work, the optimum air-demand ratio for maximum aeration efficiency in high-head gated circular conduits was studied experimentally. Results showed that aeration efficiency increased with the air-demand ratio to a certain point and then aeration efficiency did not change with a further increase of the air-demand ratio. Thus, there was an optimum value for the air-demand ratio, depending on the Froude number, which provides maximum aeration efficiency. Furthermore, a design formula for aeration efficiency was presented relating aeration efficiency to the air-demand ratio and Froude number.

Key words | aeration efficiency, air-demand ratio, conduit, high-head flow, oxygen transfer

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NOTATION

A	surface area of bubbles in control volume
C	dissolved oxygen concentration
C_d	dissolved oxygen concentration downstream of hydraulic structure
C_s	saturation concentration
C_u	dissolved oxygen concentration upstream of hydraulic structure
D	conduit diameter
dC/dt	rate of change in concentration
E	aeration efficiency
E_{20}	aeration efficiency at 20° C
f	exponent
Fr	Froude number based on effective depth in conduit
g	acceleration of gravity
K_L	liquid film coefficient
L	conduit length
P	pressure downstream of gate
P_{atm}	atmospheric pressure
Q_a	air flow rate measured through air vent
Q_w	water flow rate in conduit
t	time
T	water temperature
V	water flow velocity at gate location
$\forall$	control volume corresponding to A and C measurements
y_e	effective depth
β	ratio of volumetric air flow to water flow
φ	ratio of water cross-sectional flow area to conduit cross-sectional area

doi: 10.2166/wst.2014.305

INTRODUCTION

Oxygen is a necessary element to all forms of life. Dissolved oxygen is defined as the amount of oxygen that has dissolved into a body of water. The physical process of oxygen transfer or oxygen absorption from the atmosphere acts to replenish the used oxygen. This process has been termed re-aeration or aeration. Aerated water has more dissolved oxygen than non-aerated water. This oxygen is used by the creatures living in the body of water, such as fish and other aquatic animals. It is also used by aerobic bacteria to eliminate organic pollution. When the level of dissolved oxygen in a pond, lake, or other body of water is kept at a high level, the water is able to support life. If this oxygen saturation is depleted, either through pollution or stagnation, the body of water becomes anoxic and unsuitable for fish or other aquatic life.

Hydraulic structures can increase aeration efficiency due to an air-water two-phase flow. Air is entrained into the flow in the form of a large number of bubbles. These air bubbles greatly increase the surface area available for mass transfer. Conduit aeration is a particular instance of this. If the gate of a high-head outlet conduit is partly opened, a high velocity flow occurs downstream of it, resulting in subatmospheric pressure (Figure 1). This subatmospheric pressure causes air to be drawn through the air vent. Air that is entrained into the water is instantly forced downstream in the form of small air bubbles. The smaller the bubbles, the more air is exposed to the water, thus increasing the efficiency of oxygen being absorbed into the water.

In this study, the optimum air-demand ratio for maximum aeration efficiency in high-head gated circular conduits was studied experimentally. Knowledge of optimum air-demand ratio is important for proper high-head gated circular conduit design to obtain maximum aeration efficiency. Moreover, a regression equation was obtained for predicting the aeration efficiency of high-head gated circular conduits relating the aeration efficiency to the air-demand ratio and Froude number.

LITERATURE REVIEW

Experimental studies on air-demand ratio in closed conduits were carried out by a number of investigators (for example, Kalinske & Robertson (1943), Campbell & Guyton (1953), Haindl & Sotornik (1957), Rajaratnam (1962), USACE (1964), Wisner (1965), Sharma (1976), Stahl & Hager (1999), Speerli (1999), Speerli & Hager (2000), Escarameia (2007), Oveson (2008) and Mortensen (2009)). The air-demand ratio for the closed conduits is a function of hydraulic and geometric parameters, and for a given geometry it depends mainly on the flow types. Based on experimental data and theoretical studies, some equations have been developed by authors to determine the air-demand ratio under different flow patterns. Some of them are given in Table 1.

Recently, Ozkan *et al.* (2006, 2008, 2010), Unsal *et al.* (2008, 2009) and Tuna *et al.* (2014) conducted several experimental studies to investigate aeration efficiency in closed conduits. However, the comprehensive literature search did not identify any published analytical or physical studies on optimum air-demand ratio for maximum aeration efficiency in high-head gated circular conduits.

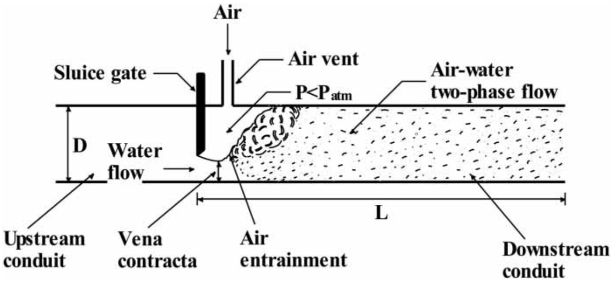

Figure 1 | Flow in high-head gated circular conduits.

BACKGROUND

Gas transfer

Oxygen is a highly volatile compound with a gas–water transfer rate that is controlled entirely by the liquid phase. Thus, the change in oxygen concentration over time in a parcel of water as the parcel travels through a hydraulic

Table 1 | Predictive equations for air-demand ratio in conduits

Equation source	Predictive relationship	Comments
Kalinske & Robertson (1943)	$\beta = 0.0066\ (Fr - 1)^{1.4}$	Hydraulic jumps within a single circular pipe
Campbell & Guyton (1953)	$\beta = 0.04\ (Fr - 1)^{0.85}$	Similar equation to Kalinske & Robertson (1943)
Haindl & Sotornik (1957)	$\beta = 0.012\ (Fr - 1)^{1.4}$	Closed rectangular conduit
Rajaratnam (1962)	$\beta = 0.018\ (Fr - 1)^{1.245}$	Two-phase flow measurements in hydraulic jumps
USACE (1964)	$\beta = 0.03\ (Fr - 1)^{1.06}$	Free-surface flow
Wisner (1965)	$\beta = 0.024\ (Fr - 1)^{1.4}$ $\beta = 0.033\ (Fr - 1)^{1.4}$	Free-surface flow Foamy flow
Sharma (1976)	$\beta = 0.09\ Fr$ $\beta = 0.2\ Fr$	Free-surface flow Foamy flow

Wherein β is ratio of volume flow rate of air to that of water (air-demand ratio) and Fr is Froude number at vena contracta.

structure can be expressed as

$$\frac{dC}{dt} = K_L \frac{A}{\forall}(C_s - C) \quad (1)$$

where C is dissolved oxygen concentration; K_L is liquid film coefficient for oxygen; A is surface area of bubbles in control volume, also a function of time; $\forall$ is control volume corresponding to A and C measurements; C_s is saturation concentration; and t is time.

Aeration efficiency

The predictive relations assume that saturation concentration C_s is constant and determined by the water – atmosphere partitioning. If that assumption is made, C_s is constant with respect to time, and the aeration efficiency E may be defined as (Gulliver *et al.* 1990)

$$E = \frac{C_d - C_u}{C_s - C_u} \quad (2)$$

where u and d are subscripts indicating upstream and downstream locations, respectively; C_u is dissolved oxygen concentration upstream of hydraulic structure; and C_d is dissolved oxygen concentration downstream of hydraulic structure. A value of $E > 1$ means the downstream water has become supersaturated. A transfer efficiency value of 1 means that full transfer up to the saturation value has occurred at the structure. No transfer would correspond to $E = 0$.

Water temperature impact on aeration efficiency

Aeration efficiency is sensitive to water temperature, and many investigators have typically employed a temperature correction factor. Gulliver *et al.* (1990) applied the theories of some investigators to mass transfer similitude and developed the relationship

$$E_{20} = 1 - (1 - E)^{1/f} \quad (3)$$

where E is aeration efficiency at the water temperature of measurement; E_{20} is aeration efficiency at 20 °C; and f is the exponent described by

$$f = 1.0 + 0.02103(T - 20) + 8.261 \times 10^{-5}(T - 20)^2 \quad (4)$$

where T is water temperature. In the present study, the aeration efficiency is adjusted to 20 °C with Equation (3).

EXPERIMENTAL METHODOLOGY

The present study was performed to determine optimum air-demand ratio for maximum aeration efficiency in high-head gated circular conduits. When the gate of the high-head conduit was partly opened, a high velocity flow occurred downstream of the gate, resulting in subatmospheric pressure. When the conduit was connected to the atmosphere through an air vent located downstream of the gate, the air was drawn through the air vent. Air entrained into the water was instantly forced downstream in the form of small air bubbles. The dissolution of oxygen into the water resulted from the air entrainment downstream of the high-head conduit. Moreover, high pressure in the high-head conduit flow systems also facilitated the dissolution of oxygen into the water. In this case, high aeration efficiency was obtained. The aeration efficiency values were calculated from Equation (2) and then adjusted to 20 °C with Equation (3).

A physical experimental setup of a circular gated closed conduit was built at Firat University Hydraulic Laboratory. All testing was performed in the physical experimental setup shown in Figure 2. The experimental setup consisted

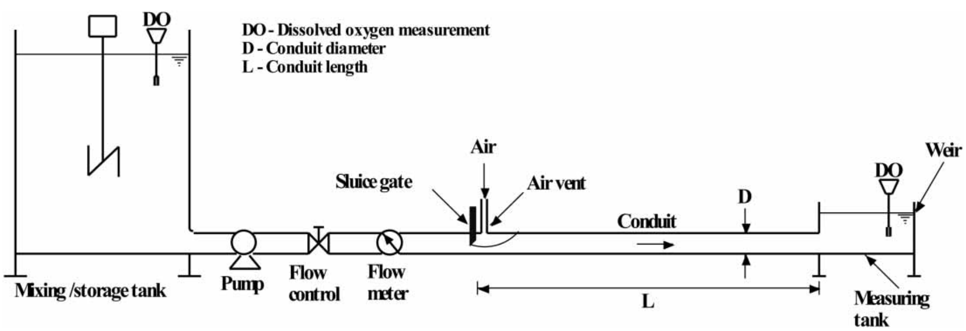

Figure 2 | Experimental apparatus.

of a water tank, dissolved oxygen meter, mixer, water pump, flow control valve, electromagnetic flow meter, sluice gate, air vent, circular conduit and measuring tank.

Mortensen (2009) has shown that the size/scale effects of air entrainment in circular closed conduits are negligible. In the present study, a 68 mm diameter pipeline was used. The conduit length (L) was 3 m. Froude numbers (*Fr*) were between 11.79 and 47.15. The Froude number was calculated by using Equation (5) using the effective depth (y_e) in the conduit

$$Fr = \frac{V}{\sqrt{g y_e}} \tag{5}$$

where V is water velocity at gate location; g is acceleration of gravity; and y_e, effective depth, is water cross-sectional flow area divided by water surface width. In the literature, the Froude number has often been based on the vena contract a section. Because high-head gated conduits involve high-velocity air-water mixture flow, to avoid the problem of determining flow depths and velocities at the vena contracta section, in this study the Froude number was based on the effective depth in the conduit.

The ratio of the water cross-sectional flow area to the conduit cross-sectional area (φ) was selected as 15 percent (see Figure 3).

Four air vents were installed immediately downstream of the gate. The air vents consisted of 16 mm inside diameter pipes that had a length of 180 mm. The sluice gate lip angle was 45°. While water entered the flume under the sluice gate, a vacuum (air entrainment) occurred at the air vent of the high-head conduit.

The air velocity rate was measured directly in the air vent and was used to determine the air flow rate. The air velocity was determined by using a Testo Model 435 anemometer (Testo, Inc., Sparta, NJ, USA). This measurement was accomplished by locating the anemometer at the center of the air vent. Each air velocity measurement was taken over a period of 60 s or longer. After obtaining a value of the air velocity, an air flow rate through the air vent was calculated. The anemometer used for air velocity measurements was accurate to $\pm(0.2 \text{ m/s} + 1.5\%$ of mv). Care was taken to ensure that the anemometer was always perpendicular to the direction of flow in the air vent to provide the most accurate measurements possible. Water flow rates were measured using a calibrated electromagnetic flow meter.

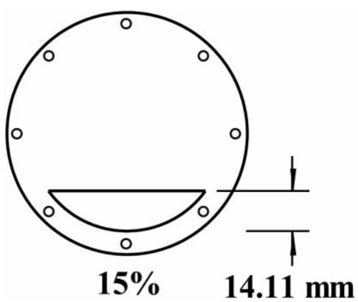

Figure 3 | Dimensions of gate.

Both the dissolved oxygen and the water temperature were measured using a calibrated WTW Model Oxi 330i oxygen meter (WTW, Weinheim, Germany). The dissolved oxygen meter was calibrated using calibration procedures following those recommended by the manufacturer. Clean tap water was used throughout the experiments. The water in the storage tank was deoxygenated using the sodium-sulfite method. Cobalt chloride catalyzed the reaction between molecular oxygen and sodium sulfite. Each experiment was started by filling the storage tank and adding sodium sulfite (Na_2SO_3) and cobalt chloride ($CoCl_2$). A stirrer was used to mix sodium sulfite and cobalt chloride with the water, until the dissolved oxygen was reduced to approximately 0.

RESULTS AND DISCUSSION

The purpose of this research was to determine optimum air-demand ratio for maximum aeration efficiency in high-head gated circular conduits. This objective was achieved by building a physical experimental setup, conducting experiments, obtaining data, analyzing the data, and presenting the results. Figure 4(a)–(f) shows plots of the aeration efficiency (E_{20}) in relation to the air-demand ratio (Q_a/Q_w) for different Froude numbers.

As can be seen in this figure, E_{20} increased with Q_a/Q_w up to a certain point and then E_{20} did not change with a further increase of Q_a/Q_w. Thus, there is an optimum value for Q_a/Q_w, depending on the Froude number, which provides maximum E_{20}.

For Froude numbers lower than 20, there was not an optimum value of Q_a/Q_w that provides maximum E_{20}. In other words, as Q_a/Q_w increased, no variation in E_{20} was observed. However, for Froude numbers between 23 and 35, an increase was observed in the optimum value of Q_a/Q_w that maximizes E_{20}. For Froude numbers of 23.57, 29.47 and 35.36, these optimum values were approximately equal to 0.30, 0.60 and 1.00, respectively.

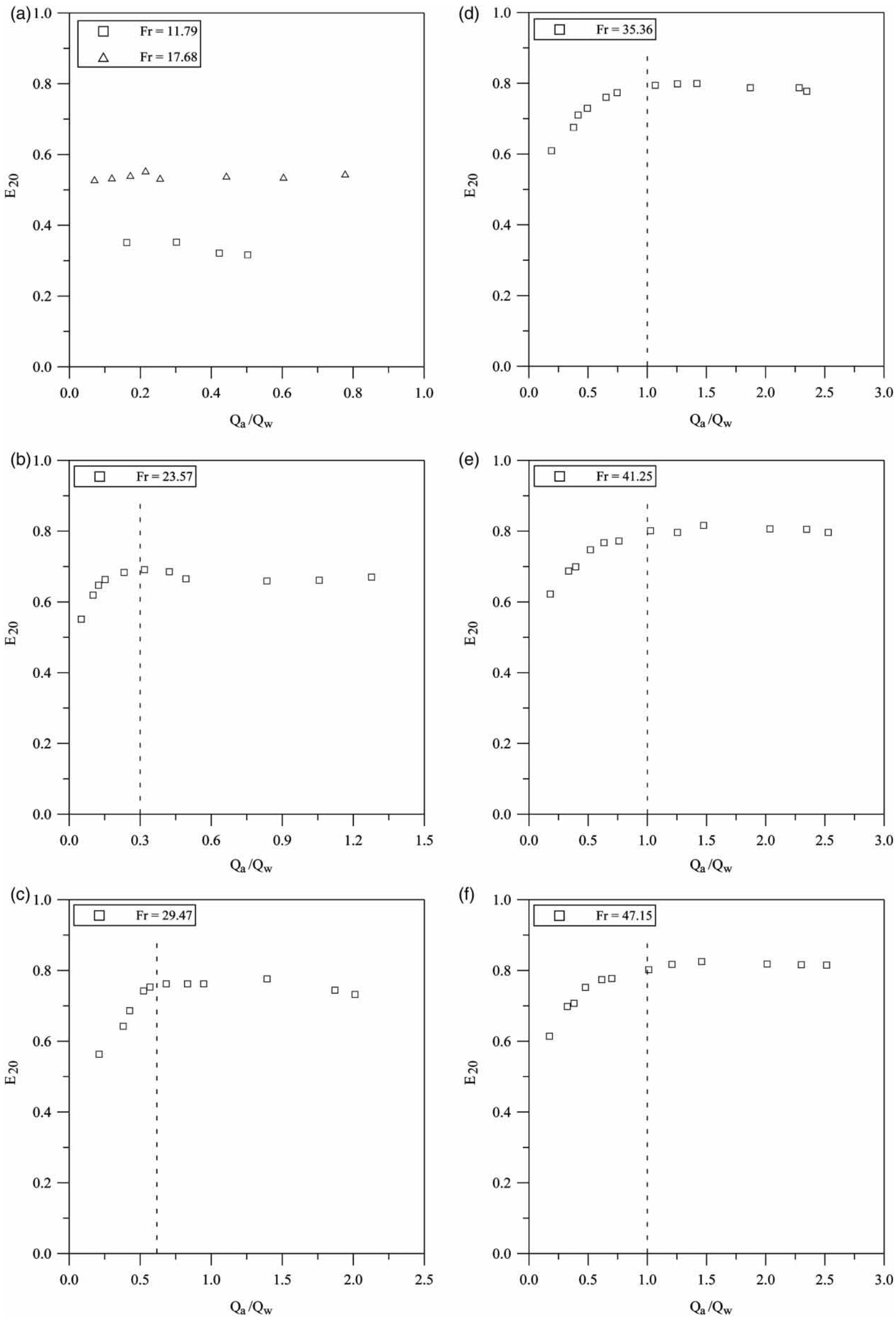

Figure 4 | Aeration efficiency as a function of air-demand ratio for different Froude numbers.

Moreover, the results showed that for Froude numbers higher than 35, maximum aeration efficiency was achieved in Q_a/Q_w of 1.00. Therefore, for Froude numbers higher than 35, the optimum value of Q_a/Q_w that provides maximum E_{20} was 1.00. This optimum value did not change with a further increase of Froude number.

DATA ANALYSIS

A design formula for aeration efficiency was developed relating aeration efficiency to the air-demand ratio and Froude number

$$E_{20} = 1 - \tanh\left[\left(\frac{Fr}{9.156}\right)^{-2.410} + 0.205\,\beta^{-0.217}\right] \quad (6)$$

where E_{20} is aeration efficiency at 20 °C; *Fr* is the Froude number based on effective depth in conduit; and β is the air-demand ratio (Q_a/Q_w).

Nonlinear regression was used to determine the constants of Equation (6). The correlation coefficient (R^2) for Equation (6) is 0.93 for the 70 data points used. This high R^2 value suggests excellent correlation. The measured aeration efficiency values were compared with those computed with Equation (6). Excellent agreement can also be seen in Figure 5.

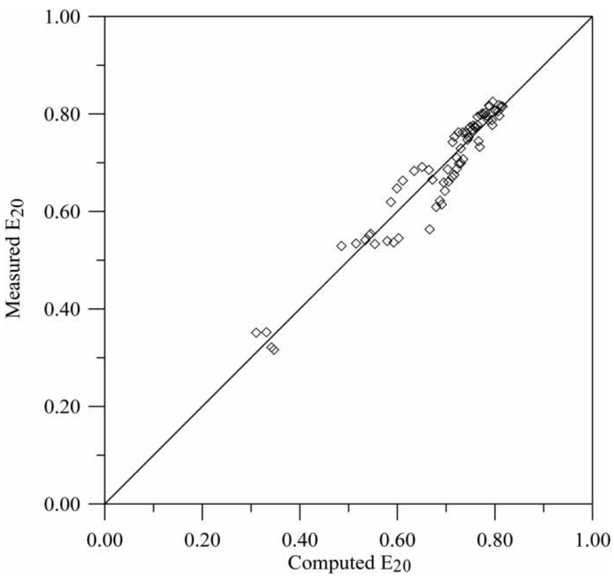

Figure 5 | Comparison between measured and computed E_{20} values using best-fit Equation (6).

SCALE EFFECTS

Great care must be taken when scaling results from models of two-phase flows as size/scale effects may exist. Previous studies have shown that the percentage of air entrainment was not affected by the size of the model. However, scaling of aeration data to prototype size is virtually impossible, largely due to the relative invariance of bubble size. Various model sizes may be necessary to determine the significance of size/scale effects of aeration efficiency in circular closed conduits between different sized structures.

CONCLUSIONS

A series of laboratory experiments has been carried out to determine the optimum air-demand ratio for maximum aeration efficiency in high-head gated circular conduits. Furthermore, a design formula for aeration efficiency was presented, relating aeration efficiency to the air-demand ratio and Froude number.

The experimental results indicate that aeration efficiency increased with the air-demand ratio to a certain point and then aeration efficiency did not change with a further increase of the air-demand ratio. Thus, depending on the Froude number, optimum values for the air-demand ratio were obtained.

For Froude numbers lower than 20, as air-demand ratio increased, no variation in aeration efficiency was observed. In other words, there was not an optimum value for the air-demand ratio. However, for Froude numbers between 23 and 35, an increase was observed in the optimum value of the air-demand ratio. For Froude numbers higher than 35, the optimum value of air-demand ratio is 1.00. This optimum value did not change with a further increase of Froude number.

The air-demand ratio higher than the optimum value did not lead to higher aeration efficiency. If the aeration system is operated above the optimum air-demand ratio, it is implied that energy consumption will increase.

Conduit geometry plays a major role in flow pattern. Therefore, additional research is needed to understand better the effect of conduit geometry on aeration efficiency.

A high level of dissolved oxygen is vital for the maintenance of healthy ponds. Using high-head gated circular conduits in pond aeration can make considerable improvements in dissolved oxygen levels. Therefore, further research is required to determine the effect of high-head gated circular conduits on pond aeration.

ACKNOWLEDGEMENT

This research has been funded by FIRAT University Scientific Research Projects Unit.

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First received 16 April 2014; accepted in revised form 24 June 2014. Available online 3 July 2014